

Evapotranspiration from Northern Semiarid Grasslands

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ABSTRACT

Management of forage production for livestock grazing on semiarid grasslands depends on water availability. Evapotranspiration (ET) was measured using the Bowen ratio energy balance method on three grasslands at Mandan, ND: a nongrazed mixed-grass prairie (prairie), a grazed mixed-grass prairie (grazed prairie), and a grazed western wheatgrass [*Pascopyrum smithii* (Rybd) Löve] site (western wheatgrass). Measurements were made from 24 April to 17 October (the growing period) in 1996, 1997, and 1998. Peak ET rates generally coincided with periods of peak biomass production and occurred between early July and early August. Peak biomass averaged 1097 kg ha⁻¹ for the prairie, 1227 kg ha⁻¹ for grazed prairie, and 1725 kg ha⁻¹ for western wheatgrass, and peak leaf area index averaged 0.38 for the prairie, 0.44 for grazed prairie, and 0.59 for western wheatgrass. Growing period (175 d) ET averaged 489 mm for the prairie, 455 mm for the grazed prairie, and 497 mm for the western wheatgrass while growing period precipitation averaged 320 mm. Evapotranspiration of grazed prairie was 7% less than nongrazed prairie and 8% less than western wheatgrass. Evapotranspiration of the nongrazed prairie and the grazed western wheatgrass were similar. The ratio of the latent heat of ET to net radiation averaged 0.25 for grazed prairie and 0.28 for prairie, suggesting that grazing changed the canopy structure and energy budget components that affected ET. These results suggest that in a semiarid environment, proper grazing of prairie grasslands conserves soil water.

BIOMASS PRODUCTION on semiarid grassland is limited primarily by lack of soil water (Rogler and Haas, 1947; Coughenour, 1985). The native grass species that occur on the mixed-grass prairie of the Northern Great Plains evolved under limited water conditions (Axelrod, 1985). These grasses often have leaf characteristics that favor water conservation, such as reduced stomatal size and distribution, surface ridging, leaf rolling, pubescence, epicuticular waxes, and early senescence (Frank et al., 1996). Hanks et al. (1968) found that when soil water was not limiting, ET for native grasses was nearly equal to pan evaporation whereas the ratio of ET to pan evaporation was 2 for oat (*Avena sativa* L.) and 1.5 for winter wheat (*Triticum aestivum* L.). Precipitation events also affect the rate of water loss from grasslands. Parton et al. (1981) showed that the greatest water loss from a shortgrass steppe occurred within 2 to 14 d after a large precipitation event.

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Proper grazing management reduces ET from grasslands by reducing transpiration losses and grazing-induced surface energy relationships that reduce evaporation (Svejcar and Christiansen, 1987; Wraith et al., 1987; Bremer et al., 2001). Cattle (*Bos taurus*) spring-grazing a tallgrass prairie site reduced season-long ET by 6.1% compared with an ungrazed site (Bremer et al., 2001). Heavy grazing of a northern mixed prairie by prairie dogs (*Cynomys ludovicianus*) increased ET over light grazing (Day and Detling, 1994). Stewart and Verma (1992), however, reported no differences in ET from grazing in a tallgrass prairie even when leaf area index (LAI) differences were large and soil water was nonlimiting. Soil water extraction by grazed and ungrazed crested wheatgrass [*Agropyron desertorum* (Fisch. Ex. Link) Shultes.] was shown to vary during the season, but cumulative soil water use was not different to 193-cm depth (Wraith et al., 1987). Generally grazed or clipped vs. ungrazed grasslands have greater soil water content available for regrowth later in the season or for use during dry periods (Owensby et al., 1970; Bremer et al., 2001; Wraith et al., 1987).

Water loss from grasslands is affected by precipitation, soil water content, air temperature, vegetation diversity and density, energy availability, and canopy structure. The canopy structure in native prairie grasslands of the Northern Great Plains is typically sparse and generally not the dominating factor in determining ET rates. Stewart and Verma (1992) confirmed the independence of latent heat flux (LE) and LAI by showing no effect on ET for LAI ranging from 0.5 to 1.7. They showed further that ET was reduced because of an increase in aerodynamic resistance to canopy water vapor flux. Ham and Knapp (1998) found that energy fluxes during senescence caused a shift from a LE- to a sensible heat (H)-driven system. Overall, grazing-induced changes in energy partitioning and canopy structure generally increase evaporative processes and decrease plant transpiration processes in grasslands.

This study reports on the ET rates for three Northern Great Plains grasslands. The objective was to determine ET rates for grazed and ungrazed native prairie in the Northern Great Plains grasslands and for a grazed site that had been seeded to western wheatgrass. Information has been previously lacking on rates and seasonal dynamics of ET for the predominately cool-season grazed grasslands of the Northern Great Plains.

MATERIALS AND METHODS

The three sites were located at the Northern Great Plains Research Laboratory, Mandan, ND (46°46' N, 100°55' W;

Abbreviations: BREB, Bowen ratio energy balance; ET, evapotranspiration; H, sensible heat flux; LAI, leaf area index; LE, latent heat flux; LEt/Rn, ratio of latent heat of evapotranspiration to net radiation.

elevation 518 m). The sites included native prairie that has been season-long continuously grazed (grazed prairie), a native prairie site that was last grazed in 1992 (prairie), and a grazed western wheatgrass site that was seeded in 1986. Grazing intensity was moderate at about 2.6 ha per steer from mid-May to early October each year for both the grazed prairie and western wheatgrass sites. The grazed prairie and prairie sites are typical of the *Agropyron* spp.–*Bouteloua* spp.–*Stipa* spp. complex of Northern Great Plains grasslands (Whitman and Barker, 1994). Point frame estimates (Levy and Madden, 1933) of vegetation composition were made on all three sites in 1995 and 1997. Vegetation of the prairie and grazed prairie sites were dominated by blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Griffiths], needle-and-thread (*Stipa comata* Trin. and Rupr.), Carex (*Carex* spp.), little bluestem [*Schizachyrium scoparium* (Michx.) Nash], side-oats grama [*Bouteloua curtipendula* (Michx.) Torr.], and Kentucky bluegrass (*Poa pratensis* L.), all of which are typically found in mixed-grass prairie ecosystems. The western wheatgrass site was 76% western wheatgrass with minor components of Kentucky bluegrass, crested wheatgrass, and broadleaf forbs. The soil is a Werner–Sen–Chama complex (loam, silt loam, and silty clay loam Entic and Typic Haploborolls) on slopes varying from 2 to 10%. The sites have not had fertilizer or herbicides applied or been burned since being purchased in 1912.

Plant biomass and green leaf area were measured about every 21 d beginning in mid-April through mid-October each year. Four representative 0.25-m² quadrats located within 40 m of the instrument tower (see below) were clipped at the soil surface and manually separated into green stems and leaf fractions. A belt-driven photoelectric area meter was used to measure the leaf area for calculating the LAI. All stem and leaf biomass was oven-dried and weighed to obtain total aboveground biomass.

Energy balance measurements were made using the Bowen ratio energy balance (BREB) system (Model 023/CO₂ Bowen ratio system, Campbell Sci., Logan, UT, USA). Water vapor fluxes were measured at the three sites from 24 April through 17 October in 1996, 1997, and 1998. One BREB system (tower) was located within each site to provide at least 200 m of fetch in all directions. The greatest distance between towers was 790 m. The towers at the grazed sites were enclosed with a fence. The vegetation inside the fence was maintained at similar height to the grazed area by using a weed-whip tool. Bowen ratio was calculated from temperature and humidity gradients measured every 2 s from arms placed at 1 and 2 m above the canopy. Water vapor flux was calculated using the Bowen ratio, average net radiation (Model Q*7 net radiometer, Radiation and Energy Balance Syst., Seattle, WA, USA), average soil heat flux calculated from two soil heat flux plates (Model HFT, Radiation and Energy Balance Syst.), and soil temperatures measured above the plates according to Dugas (1993)

and Dugas et al. (1999). The net radiometers were calibrated against a laboratory standard over a grass surface each year before use. Flux data reported here are based on measurements when net radiation was greater than 25 W m⁻² and precipitation for the daylight period was less than 6.25 mm. Applying these criteria along with times of instrument maintenance and repair resulted in ET calculations for all or part of 172 d in 1996, 174 d in 1997, and 168 d in 1998, out of a maximum of 175 d during the growing period. Water vapor concentration gradients between the two heights were measured with an infrared gas analyzer (Model 6262, LI-COR, Lincoln, NE, USA). The air stream from each arm was switched between the two analyzer cells every 2 min. Analyzers were calibrated weekly against a water vapor concentration measurement made with an HMP-35 Vaisala temperature and relative humidity probe (Campbell Sci.) located at 2-m height. Precipitation at all sites was measured with a tipping bucket rain gage. All data generated from the BREB system were captured with a model 21X data logger (Campbell Sci.). During the course of the study, instances of spurious data occurred. These data were interpolated by averaging the preceding and following flux calculations. Data modifications of this nature occurred most often near sunrise and sunset and occurred approximately 2% of the time over all years and sites.

Volumetric soil water content was determined at 3.8-cm depth with frequency-domain reflectometry methods (Model CS615 Water Content Reflectometer, Campbell Sci.) every 20 min throughout the ET measurement period. Soil temperature was measured with copper-constantan thermocouples at 3.8-cm depth. Soil water extraction from the 0- to 1.2-m depth was determined by measuring soil water content by neutron attenuation on 9 d in 1996 and 1997 and 8 d in 1998. Two access tubes were located within 5 m of the instrument towers.

Statistical analysis was conducted using SAS PROC MIXED with repeated measures (Littell et al., 1996). Evapotranspiration, microclimate, and biomass measurements were obtained over dates for each site in 1996, 1997, and 1998. The primary objective was to compare seasonal and total ET rates during the growth period from 24 April to 17 October. The covariance structure used to fit the repeated measure was a first-order autoregressive model. Sites and dates were considered fixed effects, and years were random effects, with sites × years as repeated. Means were obtained with the lsmeans statement. Significance among sites, dates, and the sites × dates interaction was tested by appropriate *F* ratios, and mean differences were compared using Tukey's test.

RESULTS AND DISCUSSION

The close proximity (790 m) of the three sites resulted in similar amounts (Table 1) and distribution of precipi-

Table 1. Growing period (24 April to 17 October) average air temperature, soil temperature, precipitation, net radiation, and volumetric soil water content for the prairie, grazed prairie, and grazed western wheatgrass during 1996, 1997, and 1998.

Year	Site	Air temperature	Soil temperature	Precipitation	Net radiation	Soil water content
		°C	°C			
1996	Prairie	15.8	15.0	313	255	0.35
	Grazed prairie	15.5	15.5	312	283	0.27
	Western wheatgrass	15.9	15.8	301	284	0.27
1997	Prairie	17.3	15.8	213	287	0.26
	Grazed prairie	17.2	16.3	216	289	0.23
	Western wheatgrass	17.2	16.6	225	290	0.22
1998	Prairie	17.2	16.6	373	300	0.27
	Grazed prairie	17.0	16.9	386	293	0.27
	Western wheatgrass	17.1	17.2	401	297	0.27

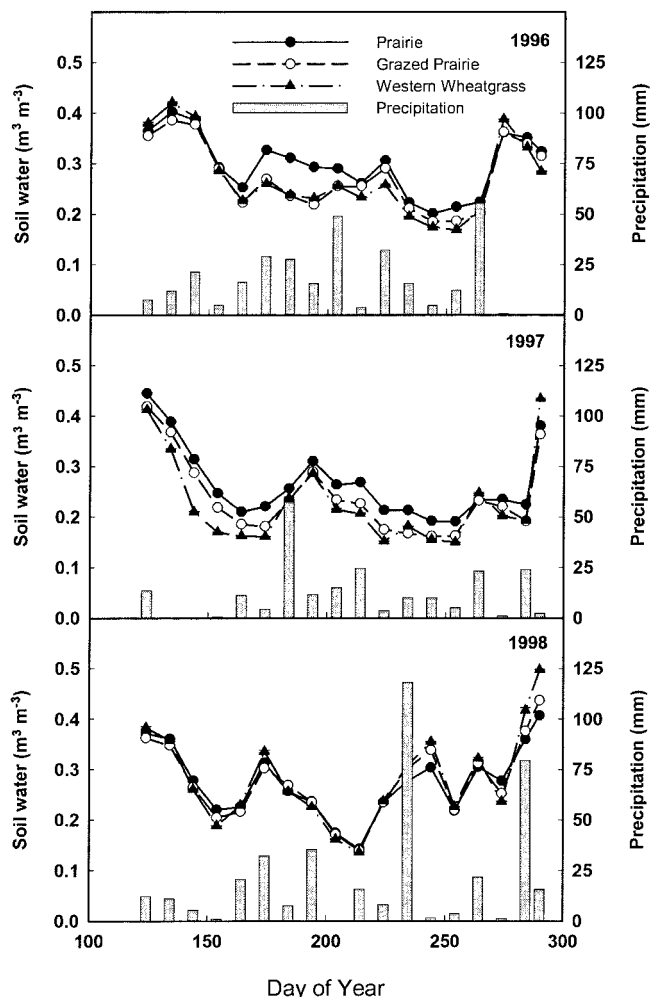


Fig. 1. Ten-day averages of volumetric soil water at 3.8-cm depth for the prairie, grazed prairie, and grazed western wheatgrass, and 10-d total precipitation received at the grazed prairie site during 1996, 1997, and 1998. Vertical error bars for soil water are standard errors of the mean and are mostly embedded within the symbols.

tation received over years; thus, precipitation received at each site during the measurement period was averaged (Fig. 1). Long-term (86 yr) annual precipitation for an adjacent weather station is 404 mm. Annual precipitation exceeded the long-term amounts by 82 mm in 1996 and 113 mm in 1998, but in 1997, precipitation was 59 mm less than the long-term average. Generally, soil water tracked precipitation received, especially when the 10-d average precipitation totals exceeded 50 mm (Fig. 1). Soil water content over sites and years averaged $0.4 \text{ m}^3 \text{ m}^{-3}$ at the beginning of the measurement period, decreased to $0.2 \text{ m}^3 \text{ m}^{-3}$ or less during at least a single 10-d period each year, and increased substantially at the end of the measurement period in 1997 and 1998, but not in 1996.

The presence of green transpiring vegetative tissue began to develop in mid-April, reached peak biomass amounts in early July to mid-August, and then decreased rapidly through late October (Fig. 2). The date of peak green aboveground biomass for the three sites was similar within years but differed over years: Peak

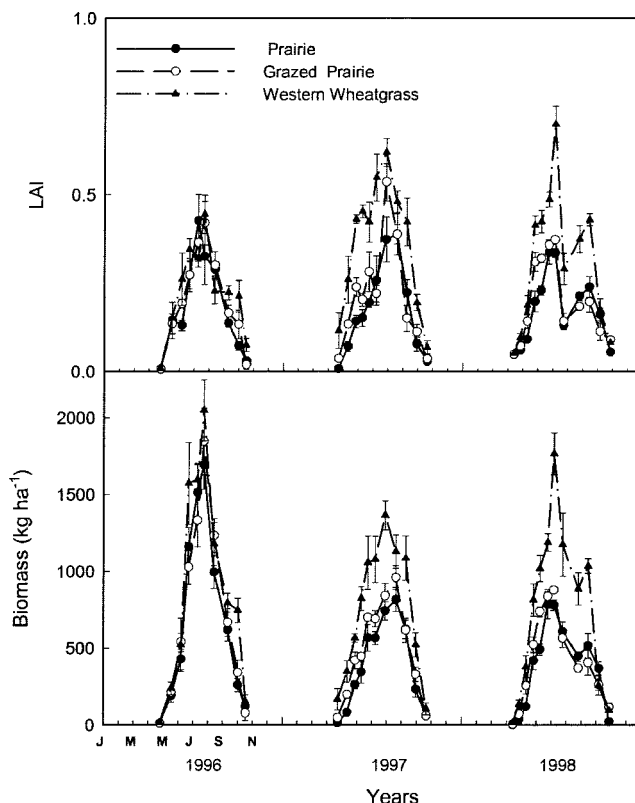


Fig. 2. Leaf area index (LAI) and green biomass for selected dates for prairie, grazed prairie, and grazed western wheatgrass in 1996, 1997, and 1998. Vertical error bars are standard errors of the mean. Statistical analysis for green biomass showed $P > F$, sites = 0.0001; $P > F$, dates = 0.0001; $P > F$, site \times dates = NS. Statistical analysis for LAI showed $P > F$, sites = 0.0009; $P > F$, dates = 0.0001; $P > F$, site \times dates = NS.

biomass occurred on sampling dates of 23 July in 1996, 8 August in 1997, and 2 July in 1998. Peak biomass production averaged 1097 kg ha^{-1} for the prairie, 1227 for grazed prairie, and 1725 for western wheatgrass. Biomass averaged across sample dates was significantly greater for western wheatgrass (725 kg ha^{-1}) compared with the prairie (450 kg ha^{-1}) and grazed prairie (498 kg ha^{-1}). Maximum LAI was closely associated with biomass accumulation within and over years (Fig. 2). Peak LAI over years averaged 0.38 for the prairie, 0.44 for grazed prairie, and 0.59 for western wheatgrass. Leaf area index averaged across sample dates was significantly greater for western wheatgrass (0.28) compared with the prairie (0.17) and grazed prairie (0.19). Biomass production from prairie grasslands in the Northern Great Plains is primarily a function of timing and quantity of precipitation (Rogler and Haas, 1947). Similarly in this study, more biomass was produced in 1996 than 1997 and 1998, and soil water content was also higher in 1996 ($0.30 \text{ m}^3 \text{ m}^{-3}$) than 1997 ($0.24 \text{ m}^3 \text{ m}^{-3}$) and 1998 ($0.27 \text{ m}^3 \text{ m}^{-3}$). Annual precipitation was greatest in 1998; however, large precipitation events occurred in August (145 mm) and October (101 mm) (Fig. 1), which was of minimal benefit for biomass production.

Measurements of net radiation, soil temperature, and air temperature for the sites in 1997 are presented as

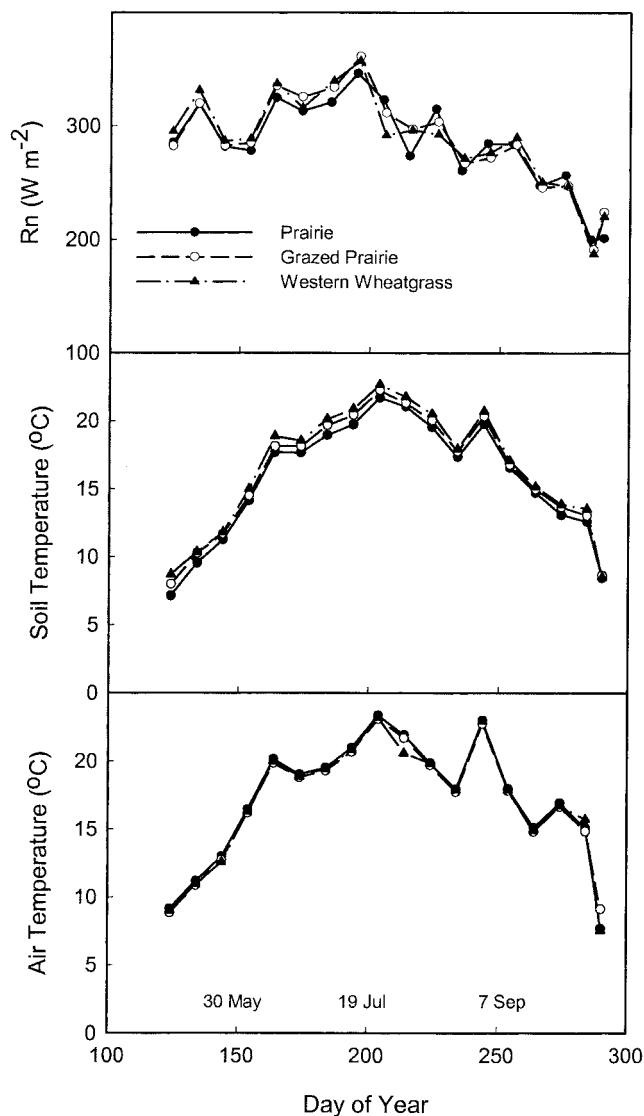


Fig. 3. Ten-day averages for net radiation (Rn), soil temperature, and air temperature for prairie, grazed prairie, and grazed western wheatgrass during the period from 24 April through 17 October 1997.

representative of all years (Fig. 3). The 10-d average net radiation exceeded 250 W m^{-2} until early autumn and then gradually declined, coinciding with decreases in plant LAI and green biomass. Average net radiation for the measurement period ranged from 286 to 302 W m^{-2} over all sites and years, except for the prairie site in 1996 when average net radiation was only 255 W m^{-2} (Table 1). Net radiation was less at each site in 1996 than in 1997 and 1998. Soil and air temperatures increased from about 8°C at start of the measurement period in April to about 22°C in July and then decreased to near the April temperatures by late October. Season-long average air temperature, soil temperature, net radiation, and soil water content were similar among treatments within years, except for net radiation in 1996 (Table 1).

The period from 29 June to 8 August 1998, a period of active plant growth, was selected to evaluate the

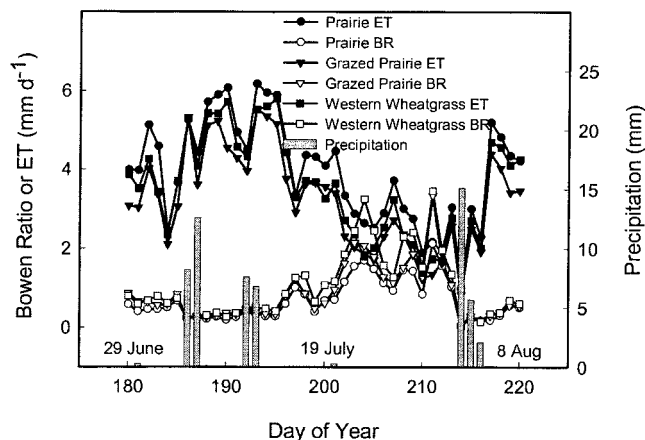


Fig. 4. Average daily evapotranspiration (ET) and Bowen ratios (BR) for prairie, grazed prairie, and western wheatgrass, and precipitation for grazed prairie for period from 29 June to 8 August in 1998.

partitioning of energy between evaporating water (LE) and heating the air above the surface (H) (Fig. 4). During this 40-d period, the Bowen ratio was nearly a reverse image of ET. Rates of ET were generally greater than 4 mm d^{-1} for the first 20 d and then declined until precipitation received on days 216, 217, and 218 provided water that increased ET to near the previous rates. During the period of high ET, the Bowen ratio was low and essentially the same for the three sites, but as ET decreased, the Bowen ratio increased because more available energy was partitioned to H. The Bowen ratio was less than 1 when ET was near or exceeded 4 mm d^{-1} and was near 2 when ET decreased to near 2 mm d^{-1} . During the period from 12 July to 2 August, when essentially no precipitation was received, a greater amount of available energy was partitioned to H than LE, but with the greater variability in data, site differences were not apparent. These results follow those of Bremer et al. (2001), who reported that with grazing, more energy was partitioned to H in a tallgrass prairie ecosystem. During this time period in 1998 (days 180–220), the prairie vegetation extracted a greater amount of soil water from the 0- to 1.2-m soil depth than during the prior and later periods.

The season-long pattern of the amount of net radiation energy used in ET, the LEt/Rn ratio, increased during spring green-up when soil water was adequate for rapid vegetative growth (Table 2). As soil water became limiting and growth conditions became less favorable, the LEt/Rn ratio decreased (Fig. 5). The site \times date interaction for LEt/Rn was not statistically significant. The 3-yr average LEt/Rn ratio was lowest for the grazed prairie (0.25) and highest for the prairie (0.28) site, but differences were not statistically different (Table 2). Hanks et al. (1968) reported ratios of 0.16 for dry soil conditions and 0.97 for wet soil conditions. Since soil water content was about the same for all sites within years (Fig. 1), the low LEt/Rn ratios for the grazed prairie suggest that less energy from net radiation was used for ET and more went to heating the soil and air (H) than for the prairie and western wheatgrass sites. Similarly, Ham and Knapp (1998) found that energy

Table 2. Total evapotranspiration (ET) and select energy budget components during the growing period (24 April to 17 October) for a prairie, grazed prairie, and grazed western wheatgrass grasslands during 1996, 1997, and 1998.

Year	Site	ET	Rn†	LEt‡	LEt/Rn
		mm	W m ⁻²	W m ⁻²	
1996	Prairie	448	255	70	0.27
	Grazed prairie	470	283	74	0.26
	Western wheatgrass	501	284	79	0.28
1997	Prairie	498	287	79	0.27
	Grazed prairie	464	289	74	0.26
	Western wheatgrass	495	290	79	0.27
1998	Prairie	520	300	87	0.29
	Grazed prairie	432	293	72	0.24
	Western wheatgrass	496	297	83	0.27
3-yr avg.	Prairie	489	281	79	0.28
	Grazed prairie	455	288	73	0.25
	Western wheatgrass	497	290	80	0.27

† RN, net radiation.

‡ LEt, latent heat of evapotranspiration.

fluxes during senescence caused a shift from a LE- to a H-driven system.

The site \times date interaction and daily ET rates were not statistically significant (Fig. 6). There was a trend to lower ET rates for the grazed prairie (2.6 mm d⁻¹) compared with the prairie (2.7 mm d⁻¹) and western wheatgrass (2.8 mm d⁻¹) sites. Maximum ET occurred at peak aboveground biomass in mid-July for all sites and was 4.7 mm d⁻¹ for the prairie, 4.4 for the grazed prairie, and 4.7 for the western wheatgrass. Daily ET partitioned into 50-d increments selected to match spring (5 May to 24 June), summer (24 June to 13 August), and autumn (13 August to 5 October) periods was not statistically different across sites; however, daily ET was greater ($P > F = 0.1$) during the summer than the autumn period (Table 3). Season-long 3-yr average ET was lower for the grazed prairie (455 mm) compared with the prairie (489 mm) and western wheatgrass (497 mm) (Table 2). Overall, ET of the grazed prairie was 7% less than the nongrazed prairie site and 8% less than western wheatgrass, and ET for the prairie and western wheatgrass sites was similar. These results were

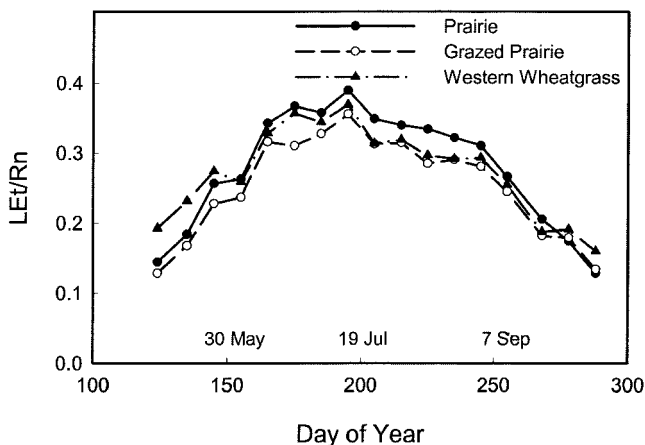


Fig. 5. Ten-day averages of ratio of latent heat of evapotranspiration to net radiation (LEt/Rn) during the 1996, 1997, and 1998 growing period for prairie, grazed prairie, and grazed western wheatgrass. Statistical analysis showed $P > F$, sites = 0.23; $P > F$, days = 0.0001; $P > F$, site \times days = NS.

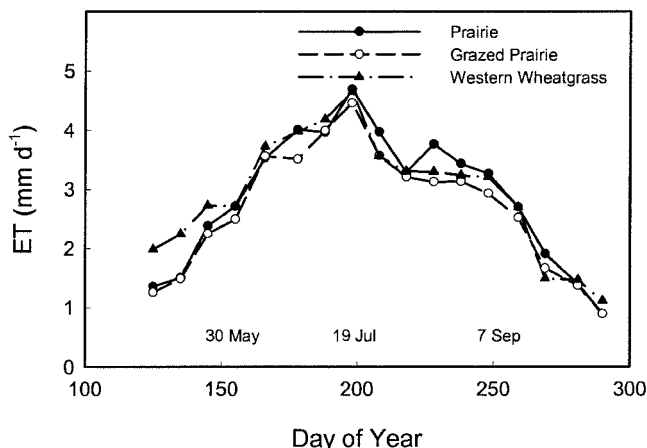


Fig. 6. Ten-day averages of evapotranspiration (ET) during the 1996, 1997, and 1998 growing period for prairie, grazed prairie, and grazed western wheatgrass. Statistical analysis showed $P > F$, sites = 0.34; $P > F$, days = 0.0001; $P > F$, site \times days = NS.

similar to the 6.1% decrease in ET reported by Bremer et al. (2001) for a grazed compared with an ungrazed tallgrass prairie site.

Cumulative ET increased in a nearly linear fashion from day 150 to 250 for all sites (Fig. 7). The overall trend was for grazed prairie to have the lowest and western wheatgrass the greatest cumulative ET throughout the measurement period. Western wheatgrass exhibited greater cumulative ET rates before day 175 (24 June), which can be attributed to the earlier growth of aboveground biomass in western wheatgrass compared with species in the native prairie. The prairie site has a greater species diversity, which includes warm-season grasses that are more productive later in the growing period than the cool-season western wheatgrass. This is supported by the increase rate in cumulative ET for the prairie site from about day 200 (19 July). The lower rate of cumulative ET for the grazed prairie site can be attributed to the removal of leaf area following day 200 and the lack of adequate soil water to support regrowth.

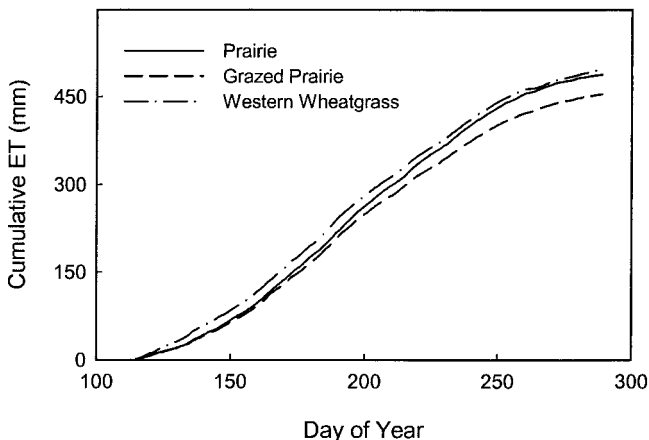


Fig. 7. Cumulative evapotranspiration (ET) during the 1996, 1997, and 1998 growing period for prairie, grazed prairie, and grazed western wheatgrass.

Table 3. Average daily evapotranspiration for prairie, grazed prairie, and grazed western wheatgrass sites during an early-, mid-, and late-season growth period during 1996, 1997, and 1998.

Period	Prairie	Grazed prairie	Western wheatgrass	Average
	mm d^{-1}			
5 May to 24 June	2.7†	2.3	2.8	2.6ab
24 June to 13 Aug.	2.9	2.9	3.0	2.9a
13 Aug. to 5 Oct.	2.4	2.4	2.6	2.5b

† Statistical analysis showed $P > F$, sites = NS; $P > F$, period = 0.09; $P > F$, sites \times period = NS. Period averages with different letters are different at 0.16 level of probability by the Tukey test.

CONCLUSIONS

Season-long ET for Northern Great Plains grasslands averaged 455 mm for a grazed prairie, 489 for a non-grazed prairie, and 497 for a reseeded grazed western wheatgrass site. Grazing native prairie grasslands reduced ET by 7% over the nongrazed prairie and 8% over the grazed western wheatgrass site. Rates of ET for the grazed western wheatgrass were similar to the nongrazed prairie site, suggesting that species composition and not grazing alone affects ET rates. Dates of peak ET coincided with dates of peak biomass and LAI and varied over years. The LEt/Rn ratio was lowest for the grazed prairie, suggesting that defoliation changed the canopy structure and energy budget components, which may have contributed to increased water loss through evaporation compared with the nongrazed prairie treatment. The grazing management imposed in this study was designed to leave nearly half of the current year biomass, which increased standing senescence vegetation and surface litter and created conditions that probably reduced surface evaporation of water. These results further suggest that in a semiarid environment, proper grazing of prairie grasslands conserves soil water.

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